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Advanced Rotorcraft Transmission (ART) Program–Boeing Helicopters Status Report

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ADVANCED ROTORCRAFT TRANSMISSION (ART) PROGRAM

BOEING HELICOPTERS STATUS REPORT

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Abstract

On May 20, 1988, Boeing Helicopters was awarded a contract by the U.S. Army Aviation Systems Command (AVSCOM) and the NASA Lewis Research Center to conduct the Advanced Rotorcraft Transmission (ART) program. The ART program is structured to incorporate key emerging material and component technologies into an advanced rotorcraft transmission with the intention of making significant improvements in the state-of-the-art (SOA). Specific objectives of the ART program are:

(1) Reduce transmission weight by 25 percent relative to SOA trends (currently in the range of 0.4 lb/hp).

(2) Reduce transmission noise by 10 dB relative to SOA.

(3) Improve transmission life and reliability, while extending Mean Time Between Removal (MTBR) to 5000 hr.

The ART contract requires Boeing Helicopters to select a baseline transmission design that is representative of a SOA production design technology and then compare this design with the advanced configuration being developed during this program. Boeing Helicopters selected a transmission sized for the Tactical Tilt Rotor (TTR) aircraft which meets the Future Air Attack Vehicle (FAAV) requirements.

Component development testing will be conducted to evaluate the high risk concepts prior to finalizing the advanced transmission configuration. A total of eight advanced technology component tests will be conducted:

- Noise reduction by active force cancellation
- Hybrid bidirectional tapered roller bearings
- Improved bearing life theory
- Transmission lube study with hybrid bearings
- Precision net forged spur gears
- High profile contact ratio noninvolute tooth form spur gears
- Parallel axis gear noise study
- Surface modified titanium accessory spur gears

This paper summarizes the results of the trade-off studies and development tests which have been completed during the first three years of the contract.

Introduction

The *ART* program is viewed as a means of providing the rotorcraft industry with a unique opportunity to advance the technology base for rotorcraft drive system via a path similar to that traditionally followed in engine development.

The *ART* program is structured in two phases. The first phase involves four contracts and is the preliminary design and component validation phase. This phase allows each contractor to develop advanced design concepts which incorporate key advanced technologies required to meet the *ART* program objectives. Trade-off studies and component test and evaluation will be conducted to support each design concept. The second phase of the *ART* Program will involve the selection of one or two contractors to conduct a demonstrator program.

Background

The Advanced Rotorcraft Transmission (*ART*) program is an Army funded, joint Army/NASA program to develop and demonstrate lightweight, quiet, durable drive train systems for the next generation rotorcraft. This program allows the participants, which include Bell Helicopter Textron, Inc., Boeing Helicopters, McDonnell Douglas Helicopter Company and Sikorsky Aircraft, to evaluate key emerging material and component technologies and novel design concepts for advancing the technology of future rotorcraft transmissions. The specific objectives of *ART* include the reduction of drive train weight by 25 percent, a reduction of noise level at the transmission source by 10 dB and an increase in reliability bv attainment of at least a 5000 hr mean time between removal (MTBR) drive system.

The *ART* program requires each participant to select a vehicle fitting into one of the two distinct next generation aircraft classes, and to demonstrate their proposed advanced concept drive trains. The two classes of aircraft are:

(1) Future Air Attack Vehicle (FAAV) - A 10 000 to 20 000 lb aircraft capable of undertaking tactical support and airto-air missions.

(2) Advanced Cargo Aircraft (ACA) - A 60 000 to 80 000 lb aircraft capable of heavy lift field support operations.

Aircraft Selection

Boeing Helicopters selected a Tactical Tilt Rotor (TTR) aircraft which meets the requirements outlined for the FAAV (nominal gross weight of 10 000 to 20 000 lb).

The TTR is a small lightweight attack tilt rotor aircraft designed to be highly maneuverable and survivable. It is also applicable to counter-air-attack and air-to-air combat missions. Its primary mission gross weight is about 17 223 lb.

In general the TTR drive system arrangement is similar to that of the V-22 Osprey aircraft. It is a twin engine configuration as shown in Fig. 1 with one engine mounted in each wing tip nacelle. The engines pivot with the rotors to convert between helicopter and airplane modes as on the V-22 aircraft. The engine size is in the 2400 shp class. A candidate engine for this engine size is a growth derivative of the T700-701C. Some additional vehicle characteristics pertinent to the ART effort are given in Table 1 and Fig. 2. Interconnect cross shafting is required between the rotors and engines so that one engine may drive both rotors in the event of an engine failure. Specifics of the accessory drives, Auxillary Power Unit (APU), and details of the lubrication and cooling systems are being developed. The transmissions will be designed to provide at least 30 min of operation after loss of lubrication or gear/shaft damage. In general, all subsystems of the TTR will provide both crashworthy and damage tolerant characteristics.

Trade-Off Studies

Computer models were used to develop a reference aircraft design so that the influence of the advanced technology improvements on aircraft size and performance could be evaluated. In the early stages of this program a few key parameters were used to develop the drive system design. As the design progressed, detailed rotor and engine performance data were entered to improve the precision of the calculations. The computer models were used to discover broad trends early in the design process and to determine the effects of relatively small modifications as the design is evolved.

During the early development of the *ART* drive system, comparisons and trade-off studies were conducted between novel transmission configurations with high payoff potential. In addition to the transmission configuration, advance technology features such as high temperature materials, novel gear and bearing designs, composites, and lubrication methods were also evaluated relative to achieving the goals of the *ART* Program. The Boeing Helicopters approach included the study of the following transmission configurations:

(1) Selfaligning Bearingless Planetary (SABP) Configuration - The basic attributes of this configuration are the elimination of planet carriers and bearings and the static gear load cancellation through aligned gear meshes.

(2) Split Torque Configuration - The basic attribute of this configuration is the multiple parallel torque load paths which provided design/flexibility in optimizing the gear mesh loads.

(3) Conventional Single Stage Planetary Configuration - The basic attributes of this configuration are its compact geometric arrangement and the extensive broad experience with effective gear mesh load sharing.

Extensive studies were conducted on each of these configurations to establish weight trends, reliability factors and predicted noise characteristics. This data was then compared with the baseline data established for current SOA transmissions. For Boeing Helicopters, the SOA baseline data was the CH-47 and YUH-61 drive systems. A selection methodology was developed to rank the three configurations based on the trade studies and comparisons. The results of this selection process are summarized in Fig. 3 and discussed in detail below.

1. Selfaligning Bearingless Planetary Configuration

The low weight (0.306 lb/hp) and reduced number of bearings in this configuration appear to be the most significant advantages of this design. All of the other ranking factors are considered very high for achieving the ART program objectives. The critical indexing of three gears on each of six planet spindles appears to be the major concern of this design. Problems with current gear manufacturing would make this requirement difficult to achieve. In addition, any indexing problems would result in high noise and vibration and unknown dynamic loads. Although the planet gear bearings are eliminated, a new type of bearing problem will be created since each spindle rotates within two sets of rings. The long-term performance of this transmission configuration is unknown. The potential for improving the MTBR with this design is also quite low. Overall, this design offers many potential problems for a relatively low return on benefits. Therefore, this design was not given further consideration.

2. Split Torque Configuration

Overall this design showed considerable promise in many areas except weight (0.340 lb/hp). The projected weight of this design is the highest of all configurations studied. The biggest unknown with this configuration is the ability to split the torque uniformly (50/50) between the rotors under actual flight conditions. To ensure an even

split, additional components would have to be added which would further increase weight (and numbers of parts required) while reducing the other benefits. Therefore, this design was also rejected.

3. Single Stage Planetary Configuration

Based upon the proposed ranking methodology, this design appears to have the greatest potential for achieving all of the objectives of the *ART* program. Although the transmission trend weight (0.317 lb/hp) is not the lowest, it appears that further work could reduce the weight and achieve the goal of 0.30lb/HP or less. The use of single and double helical gears will significantly reduce noise and vibration. Also, this configuration achieves the best improvement in the MTBR when compared to the baseline. Although the system still has several potential problem areas, it appears to be best suited for achieving the overall objectives of the *ART* program relative to the other configurations considered.

Based upon these evaluations, Boeing Helicopters selected the single stage planetary configuration as the TTR drive system concept most likely to achieve the *ART* program objectives. The basis for selection was a combination of weight, noise and reliability considerations. The basic configuration is shown in Fig. 4. The configuration allows for extensive application of hybrid (ceramic rolling element) bearings, bidirectional tapered roller bearings; advanced gear and bearing materials; double helical planetary gear mesh; and helical gearing throughout the rest of the drive train. The speed reduction of approximately 5.1:1 taken in the planetary stage is greater than typical rotorcraft planetary reductions which are usually in the range of 3:1 or 4:1. This configuration provides a lightweight compact design and high reliability gains are expected through a significant reduction in the number of parts.

Effect of Transmission Improvements

Following the selection of the *ART* configuration, studies were conducted to determine what effects improvements in transmission weight would have on aircraft size, performance and operating cost. With the basic parameters of the baseline TTR aircraft established, it was possible to examine the effects on performance of the baseline vehicle by simply reducing the transmission weight without resizing the whole aircraft. Similar studies were also conducted to evaluate mission performance and expected aircraft flyaway cost based upon the expected improvement in the drive system.

The aircraft performance was evaluated by retrofitting an existing baseline vehicle model with the advanced transmission design. In this case, the empty weight reduction for the vehicle was used to increase the useful load capacity of the vehicle without increasing the gross take-off weight. This useful load increase can be applied to fuel or payload. If it is used to increase the fuel load, an extension of the radius of action can be achieved as shown in Fig. 5. This figure illustrates a significant improvement in aircraft mission performance when compared with the original baseline data, shown in Fig. 2.

The advanced transmission technology was also applied to a totally new aircraft design so that the drive system benefits could be incorporated into the basic vehicle sizing. In this case, the transmission weight reduction has a spin-off effect yielding a lower gross weight to perform the same mission. The effect on major aircraft design parameters is illustrated in Fig. 6. The advanced drive system contributes significantly to a reduction in vehicle gross weight and empty weight. Also, the engine size and power can be reduced from 4038 to 3724 hp. The reduction in vehicle gross weight and engine power rating

factor into the acquisition cost of the vehicle.

In addition to improved aircraft performance, the *ART* technology also impacts the TTR aircraft flyaway cost. Cost studies were conducted comparing the baseline and a modified *ART* aircraft. To evaluate the effect on flyaway cost, a series of trend studies were conducted based upon the assumptions defined in Table 2 concerning the parameters that influence the economic aspects.

The results of these studies are summarized in Figs. 7 and 8. In Fig. 7, the greatest cost reduction occurs for the dynamic system due to the improvements identified in the *ART* drive system. This results in a 14 percent reduction in drive systems cost based upon a 600 TTR aircraft production run. The reduction in drive system cost also had some smaller effects on the engines (7 percent) and airframe (2 percent) cost reductions. Incorporating the component cost breakdown into the flyaway cost, yields a 4 percent cost reduction. Although the drive system cost reduction is quite significant, the drive system only makes up 10 percent of the total aircraft cost. The cost impact of *ART* will still result in a savings of approximately $250,000 per aircraft or a total program savings of $150,000,000 for a 600 A/C production run. This cost savings represents a significant payback on the cost of the *ART* technology program. It is anticipated that additional cost savings will be achieved when the MTBR improvements are included in the operating cost of the TTR aircraft. The results of this study shown in Table 3 indicates a 27 percent reduction in life cycle cost when *ART* technology is incorporated. This is an additional savings of $152,552,000 for a 600A/C fleet.

The above mission analysis studies indicate that significant improvements in TTR aircraft sizing, performance and cost can be obtained by incorporating the benefits of the *ART* program. These improvements can be achieved by retrofitting an aircraft with an *ART* drive system which resulting in either an increased mission radius of 17 percent or increasing the aircraft payload by 18 percent. Even greater improvements can be achieved by applying the *ART* drive system to a new aircraft design which will have a greater impact on aircraft gross weight and engine power rating requirements. Additionally, the *ART* program will also have a significant impact on the acquisition and operating cost of the TTR aircraft. Conservative estimates indicate a potential cost savings of more than $300 million on a production run of 600 TTR aircraft or an approximate cost reduction of $0.5 million per aircraft.

Component Development Testing

To achieve the objectives of the *ART* program, Boeing Helicopters identified a set of advanced technology components which require evaluation prior to incorporation into the *ART* drive system. These new technology components are essential for achieving the reduction in weight and noise and the increase in MTBR that are projected when these components are incorporated into the transmission design. The following sections describe the purpose and status of the eight component development programs which are being conducted by Boeing Helicopters as part of the *ART* program. These advanced technology component test programs, as illustrated in Fig. 9, are as follows:

(1) Noise reduction by active force cancellation

(2) Hybrid bidirectional tapered roller bearings

(3) Improved bearing technology

(4) Transmission minimum lube study with hybrid bearings

(5) Precision net forged spur gears

(6) High profile contact ratio non involute tooth form spur gears

(7) Parallel axis gear noise study

(8) Surface modified titanium accessory spur gears

1. Noise Reduction by Active Force Cancellation

In order to achieve a 10 dB reduction in transmission noise, a new concept called Active Noise Cancellation (ANC) is being evaluated. This concept uses electronically generated sound to cancel unwanted noise. The principles of constructive and destructive interference form the scientific basis for the process. The noise and vibration produced by a helicopter transmission generally is periodic or repetitive in nature. An electronic microprocessor then analyzes the noise or vibration wave form and then produces an antinoise wave form which is exactly 180° out of phase. This concept is illustrated in Fig. 10. The electronic microprocessor continues to compare how well the antinoise sound is canceling the noise and makes corrections after each cycle. Boeing Helicopters is working with Noise Cancellation Technologies on this project.

This work is proceeding in two phases. The first phase, which has been completed, demonstrated that the concept should work in the frequency range of noise and vibrations produced by a typical helicopter transmission. Initial testing was conducted using a small planetary gearbox which produced planetary frequencies and sidebands in the 1700 Hz range. A photo of the test setup and examples of typical uncanceled and canceled noise data are shown in Fig. 11. Based upon these preliminary tests, noise reductions of 10 dB or greater were achieved.

The next phase of this program is to conduct similar testing using a full-scale helicopter transmission. Testing of a CH-47 forward transmission has begun and these tests will determine the effectiveness of Active Noise Cancellation for achieving a significant reduction in noise and vibration being produced by a helicopter transmission.

2. Hybrid Bidirectional Tapered Roller Bearing

The selected ART drive system shown in Fig. 4 makes extensive use of single helical gears. The use of a thrust type bearings are required to react the thrust produced by the single helical gears. Boeing Helicopters has selected bidirectional tapered roller bearings to react to the thrust and radial loads at one end of each shaft. The other end of the shaft is supported by a cylindrical roller bearing that reacts to the radial load and allows for axial growth due to loading and thermal expansion.

Bidirectional tapered roller bearings have been developed by the Timken Company for use in turbine engines. The design concept is being expanded for use in the ART transmission and will include the features illustrated in Fig. 12. This type of bearing offers high load and speed capability within a single row bearing which can also react thrust in two directions. In addition, the problem of preloading a set of tapered roller bearings will be eliminated and the problem of varying preload setting due to thermal growth will also be eliminated. The proposed bearing design will be a hybrid which incorporates the use of ceramic rollers and PolyEther-EtherKetone (PEEK) composite cages to reduce dynamic loads, increase performance under marginal or oil-off operation and also increase the fatigue life for this type of bearing.

The Timken Company has completed the fabrication of test bearings and testing of the components has started. Testing will compare the differences between a standard bidirectional tapered roller bearing and the hybrid design.

3. Improved Bearing Technology

Significant improvements in bearing technology are required to achieve the goals of weight reduction and increased MTBR's. The work planned in this area

addresses the previously mentioned area of developing the bidirectional tapered roller bearing and the following additional work:

(1) Improved life prediction theory

(2) Surface interaction of rolling element materials

(3) Optimized design of hybrid ball and roller bearings

A computer program is being developed by SKF which will incorporate a new bearing life theory and the traction properties of various material combinations to better predict the service life of transmission bearings. With this model, it is hoped that bearing fatigue lives can be optimized to achieve the desired goal of a 5000 hr MTBF gearbox. In support of this work, traction tests were performed under stress, temperature, lubrication and surface roughness conditions which simulated those of the *ART* transmission bearings. All traction tests were performed at a maximum Hertz stress of 294 ksi, which corresponds to the stress of the heaviest loaded roller. The ball on disk traction test rig as shown in Fig. 13.

Based upon the materials selected for the *ART* transmission, the material combinations shown in Table 4 were selected for the traction tests.

The ball specimens used in the traction tests were fabricated from 13/16-in.-diameter M-50 Grade 10 balls and similar geometry silicon nitride balls were made of Norton NBD-100 material. The disk test specimens had an outside diameter of 3.75 in. and a thickness of 0.5 in. The surface finishes of the disk test specimens were measured to be less than 4 μin. The ball test specimens had measured surface finishes less than 0.5 μin.

The traction tests were run at a rolling speed (disk peripheral velocity) of 250 in./sec. The temperature of the chamber enclosing the ball and disk was controlled to produce a range of λ (film thickness/composite surface roughness) values representative of transmission operating conditions. The λ values calculated for the ball-on-disk test rig at various traction test temperatures are summarized in Table 5.

Tests were conducted using lubricants meeting the MIL-L-23699 and DOD-L-85734 specifications. The lubricants were drip fed onto the disk near the ball/disk contact at the rate of approximately one drop per second. This oil drip rate was found to provide ample lubrication at the ball/disk contact resulting in full EHD film formation.

Table 6 summarizes the maximum friction coefficients for 29 traction tests performed for the various material combinations evaluated under common test conditions. In nearly all cases tested, the traction coefficients decreased with increasing temperature. The trend of decreasing friction coefficient with increasing temperature was not anticipated prior to testing. It was expected that as the temperature increased, the EHD film thickness would decrease resulting in lower λ values and consequently more surface asperity contact and higher friction coefficient. However, since this same trend has been observed in other lubricant tests, it is believed that this effect is real.

In the lubricated tests, the lowest maximum friction coefficient measured was 0.021 for the ceramic ball/M50 NiL disk combination at 400 °F. Of the three disk materials tested, M50 NiL produced the lowest friction coefficient in all but one test case. In general, the friction coefficients measured for the three disk materials were lower with the ceramic ball than the M50 ball.

The following conclusions and observations were made based on the traction test results:

(1) M50 NiL provided the lowest friction of the three disk materials tested.

(2) The friction coefficients were generally lower with the ceramic ball than with the M50 ball.

(3) At very high λ's (10), the lubricated traction curves were virtually identical for all material combination tested.

(4) Friction coefficients generally decreased with increasing temperature in spite of the lower calculated λ values.

(5) In unlubricated tests, the peak friction coefficients were an order of magnitude greater than those observed with oil lubrication.

(6) M50 NiL provided the lowest unlubricated friction followed in turn by TDC coated M50 and VASCO-X2.

The above data will be used to improve the life prediction of bearings and also to optimize the design of hybrid ball and roller bearings. These bearings will then be tested in the next component test plan.

4. Transmission Minimum Lube Study with Hybrid Bearings

Hybrid (ceramic) rolling element bearings have the potential to offer significant improvement in bearing performance for future transmissions. These benefits include longer fatigue life, good marginal lube performance and reduced weight. Figure 14 provides a list of additional properties of hybrid bearings and shows the fabrication sequence of ceramic balls. This figure also illustrates the significant reduction in centrifugal ball loads which can occur by just changing from steel to ceramic. For very high speed bearings, this can result in a significant improvement in bearing fatigue life.

The main reason for using hybrid bearings in the *ART* transmission is primarily to take advantage of the potential to operating the bearings at reduced oil flow rates. Initial hybrid bearing results indicate that good marginal lube performance and reduced friction can be achieved. These factors can result in a reduction in the lubrication flow rates to all bearings. In combination with lighter weight, longer fatigue life and corrosion resistance, it is expected that the use of hybrid bearings can make a significant impact toward achieving the design goals of the ART transmission.

Boeing Helicopters plans to test the hybrid bearing concept in a CH-47 engine transmission to compare these results with standard bearing operation. Extensive testing is planned to evaluate the bearings over a wide range of operating conditions. Included in these tests will be the reduction in oil supply, the use of new lubricants and the determination of heat generation rates.

5. Precision Net Forged Spur Gears

Precision near net shape forging of helicopter gears offers several advantages in the design of advanced rotorcraft transmissions because the process has the potential for:

(1) Reducing machining, material and energy requirements

(2) Increasing fatigue life

(3) Improving the endurance limit.

The process is expected to contribute directly to reducing weight and extending service life.

The key to successful precision forging is the design and manufacture of the forging dies to precise dimensions, typically by EDM techniques. Corrections must be built into the dies to accommodate the distortions which occur during the forging process.

Forging flash and the back side of the gear are machined by holding the gear

on the pitch line in special chucks called nests. A negative of the tooth form locates the gear forging ensuring correct relationship between machined faces, center holes, and the forged teeth.

reduction

When gears are manufactured from conventional forged blanks, the gear teeth are actually cut into and across the forging flow lines, as shown in Fig. 15. Conversely, when a gear blank is near net shape forged, the rough shape of the gear teeth are produced in the forging operation developed by the Eaton Corporation. Therefore, the grain flow is around the contour of the gear teeth themselves, as shown in Fig. 16. It is this conformity of the forging flow lines which provides the improvement in fatigue characteristics, most notably in bending fatigue but also in surface fatigue.

The approach for achieving the objective of this program is to develop, design, and manufacture tooling compatible with the standard Boeing Helicopters single tooth fatigue test gears, manufacture a representative batch of these test gears, inspect the geometry and metallurgy of the gears, and test their bending fatigue load capacity relative to the capacity of similar, conventionally manufactured gears. The Eaton Corporation designed the dies and forged the test gear blanks. In addition, a batch of test gears is being manufactured from an advanced VASCO steel with a nickel additive for improved fracture toughness and basic load capacity. A large data base from prior testing of these standard test gears is available and will provide a good statistical comparison.

6. High Profile Contact Ratio Noninvolute Tooth Form Spur Gears

The objective of this program is to design, build, and test a set of spur gears which utilize a high profile contact ratio noninvolute tooth form (HCR-NIF) to provide a relatively constant curvature radius along the tooth profile while yielding a profile contact ratio of at least 2.1. This configuration allows the use of a high reduction ratio in a single stage while simultaneously minimizing noise generation and improving surface load capacity. The high profile contact ratio (HCR) provides a   in the loading on any single tooth through improved load sharing. As Fig. 17 shows, by extending the length of the teeth and changing the tooth proportions and pressure angle, the total transmitted tooth load is shared among alternate two and three pair contact conditions.

Unfortunately, the extended contact associated with HCR involute gears also results in higher sliding velocities and lower relative curvature radii at the extremes of contact thus reducing both the scoring resistance and surface durability of the gears. This effect is largely counteracted by the improved load sharing and thus some net benefit in load capacity is obtained. The addition of the noninvolute tooth form (NIF) tends to improve the relative curvature radii at the extremes of contact and thus further enhance the load capacity of the gear set while retaining the noise level improvements.

The test program is aimed at investigating the performance of high profile contact ratio - noninvolute form gearing, the relative noise characteristics, and the load capacity. A set of conventional, standard contact ratio gears of at the same reduction ratio and center distance will be used for comparison.

Two sets of spur gears will be designed to operate on the 10 in. center distance Gear Research Test Rig in an overhung configuration. One set of gears will have standard involute tooth form and proportions while the second will utilize HCR-NIF teeth.

Previous NASA testing[1] of small gears using this tooth form indicate, as shown in Fig. 18, that the surface load capacity is substantially greater than that of conventional involute gears and that the bending load capacity (at equal

stress) is at least equal to that of standard involute gears. The scoring resistance of HCR-NIF gears, however, does appear, as Fig. 19 indicates, to be lower than that of equivalent standard involute gears. The lower scoring load capacity performance may be due to inadequate profile modification on the small test gears. This design effort will concentrate on modifying the HCR-NIF gears so that the scoring load capacity is improved.

7. Parallel Axis Gear Noise Study

The problem of gear noise in helicopter transmissions is ever present. The primary exciting forces which produce the noise are the gear teeth meshing forces. While this is an oversimplification, since many factors influence transmission noise in addition to the gear mesh forces, the simple fact remains that if the basic exciting forces are reduced and no amplifying factors are present, the overall noise level of the system will be reduced.

Among the several ways in which the gear tooth meshing forces may be reduced, two of the most directly applicable to helicopter transmissions are modifications to the form of the teeth and the overall contact ratio. Both approaches are attractive for aerospace applications since, unlike other "treatment" methods, which are applied with penalties to either system weight or performance, these approaches have the potential for reducing noise without causing any increase in overall system weight or reducing performance. In fact, both approaches also offer the possibility of actually providing improved gear performance in terms of longer life, higher load capacity, improved reliability, and reduced weight while simultaneously reducing noise levels.

The objective of this program is to determine, by controlled testing and actual noise measurements, the effect of changes in the profile, face, and modified contact ratio and gear tooth form, separately and in combination, for spur and helical gears.

The specific gear configurations to be tested are shown in Table 7. While a wide range of specimens is shown, they will all be configured as nearly alike as practical, within the limitations imposed by manufacturing considerations and the test stand. The test gears are compatible with and will be tested in the NASA Lewis Gear Noise Test Facility, Fig. 20.

8. Surface Modified Titanium Accessory Spur Gears

Accessory gears in many helicopter applications, especially for high power aircraft, are sized more by geometric requirements than by load capacity. In general, the pitch diameters of such accessory gears are determined by the restraints imposed by the overall design of the gear box. Therefore, as the basic gear box becomes larger, the accessory gears are often designed with very small face/diameter ratios and are heavier than required to transmit the power required by the individual accessories. Since there are practical limits on how small the face width can be on a large diameter gear, such gears are often weight inefficient. One way of reducing the weight of these gears would be to use a material which has a lower density than the steel typically used.

Titanium is one such material, however, it has not gained wide spread use because it performs poorly in dynamic, frictional applications. Titanium gear teeth suffer from a rapid galling type failure, despite the best lubrication. Recent advances in surface modification processes, such as ion implantation, Fig. 21, however may make it possible to treat the surface of titanium gears to minimize the galling problem. If this approach is successful, a definite weight advantage can be obtained. Thus the objective of this program is to design, build, and test a set of spur gears which utilize surface modified titanium as the gear material.

The test program is aimed at investigating the performance and noise characteristics of surface modified accessory gears. Particular items of interest are relative scoring and surface durability capacities of titanium gears compared to a set of conventional steel gears at the same reduction ratio and center distance.

Two sets of spur gears have been designed to operate on the 6 in. center distance Boeing Helicopters Gear Research Test Rig an the overhung configuration. One set of gears will be designed for durability testing while the second set will be designed for scoring testing. The durability test gears are a 1.67:1 ratio set while the scoring test gears are a 1:1 ratio set.

The gears are being manufactured from Ti-6Al-4V Titanium alloy in accordance with the contractor's normal practice so that they are fully representative of aircraft gears. However, the gear tooth profiles will be surface modified by two candidate processes in an effort to avoid the galling problems which have limited the application of Titanium gears in power systems.

A complete inspection data history (lead, profile, spacing, runout, and finish) will be compiled for each gear set. Test slugs will be included in the gear heat treat lot so that metallurgical characteristics may be defined.

Summary of Results

Work being conducted by Boeing Helicopters under the Advanced Rotorcraft Transmission Technology Integrated Demonstration program will provide significant advancements in the state-of-the-art for future rotorcraft drive systems. This work is needed to keep pace with the design goals of future aircraft. Significant reduction in drive system weight and noise and increases in the MTBR will be deomonstrated during this program. Preliminary design studies completed by Boeing Helicopters indicate that all of the ART goals can be achieved through the use of novel designs and advanced through the use of novel designs and advanced technology components. These items contain some risk and will require thorough evaluations during the ART program to insure that they will provide the needed performance improvements.

Boeing Helicopter has selected a single stage planetary main rotor transmission for a TTR aircraft to demonstrate the performance improvements developed under the ART program. In addition, projected reductions in flyaway and operating cost have been made which show significant reductions that will more than pay back the cost of the ART program. Eight key advanced technology component test programs are underway to evaluate component performance and validate the technology for incorporation into the ART. The testing is expected to be completed by early 1992.

Acknowledgement

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Reference

1. Townsend, D.O., et al. "Evaluation of High-Contact-Ratio Spur Gears With Profile Modification" NASA Conference Publication 2210, AVRADCOM Technical Report 82-C-16, July 1981, pp. 519-531.

Table 1. Baseline Aircraft Parameters

Primary Mission Gross Weight, Lbs	17,223	
Structural Design Gross Weight, Lbs	16,155	
Wing Span, Ft	36.2	
Wing Area, Ft^2	224	
Wing Loading @ SDGW, PSF	72	
Rotor Diameter, Ft	25	
Disc Loading @ PMGW, PSF	17.5	
Number of Blades Per Rotor	3	
Rotor Solidity	0.117	
Engines	Two GE 700-701C	
Maximum Power SLS Installed, SHP	2019 (Each)	
Condition:	**Cruise**	**Hover**
Output Shaft Power Rating, HP	1955	2444
Transmission Input Rating (AEO), HP	1939	2424
Mast Output Torque, Ft-Lb	21,396	21,396
Main Rotor Speed, RPM	480	600

Table 2. Initial Values to Establish Baseline Cost Comparison	
Profit Factor	10%
Number of Prototypes in Development Program	3
Total Number of Production Aircraft	600
Number of Ground Test Articles	1
Number of Flight Test Hours	2000
Time Between Engine Overhauls, Hrs	5000
Time Between Dynamic System Overhauls, Hrs	3500
Transmission System Used Entire Flight?	Yes
Annual Interest Rate on Capital	10%
Depreciation Period (Yrs)	25
Residual Value	$ 0
Annual Utilization (Flight Hrs per A/C)	420
Customer Aircraft Buy	60 per Year

Table 3. Comparative Cost[1] Estimates		
COST ELEMENT	**BASE**	**ART**
Line & Base Level Maintenance Labor	32,565	24,486
Replenishment Spares	245,079	184,275
Depot Labor	11,753	8,837
Fuel & Lubricants[2]	-	(73,340)
Initial Spares	36,178	28,765
Total:	325,575	173,023
Life Cycle Cost Savings of **ART**	$152,552 (26.9%)	

NOTES: [1] Costs Are Shown in 1988 Dollars

[2] Cost Savings Resulting From **ART** Improvements

Table 4. Ball & Disk Test Combinations	
BALL	**DISK**
M50	M50 with Armoloy TDC Coating
M50	M50 NiL
M50	VASCO X2
Silicon Nitride	M50 with Armoloy TDC Coating
Silicon Nitride	M50 NiL
Silicon Nitride	VASCO X2

Table 5. Lambda Values for Ball & Disk Testing	
Temperature °F	LAMBDA
70	9.71
150	2.71
200	1.53
280	0.80
350	0.51
400	0.39

Table 6. Maximum Friction Coefficients

Temperature	70 °F	70 °F	280 °F	400 °F
Materials (Ball/Disk)	Unlube	Lube	Lube	Lube
M50/M50 + TDC	0.52	0.064	0.046	0.036
M50/M50 NiL	0.50	0.063	0.029	0.022
M50/ VASCO X2	0.55	0.063	0.044	0.045
Si_3N_4/M50 + TDC	0.41	0.064	0.031	0.026
Si_3N_4/M50 NiL	0.40	0.063	0.033	0.021
Si_3N_4/ VASCO X2	0.47	0.063	0.037	0.025

Table 7. Proposed Gear Noise Test Matrix

Test	Contact Ratios			Tooth Form	Type[1]
	Profile	Face	Mod		
Baseline Spur	1.25	0.00	1.25	Involute	S
HCR INV	2.15	0.00	2.15	Involute	S
Baseline Helical	1.25	1.25	1.77	Involute	H
Double Helical	1.25	1.25	1.77	Involute	H
HCR INV	1.25	1.75	2.15	Involute	H
HCR INV	2.15	2.25	3.11	Involute	H
NIF Baseline	1.25	0.00	1.25	Non Involute	S
NIF HCR	2.15	0.00	2.15	Non Involute	S

NOTE: [1] S = Spur, H = Helical

Figure 1.—TTR artist's concept

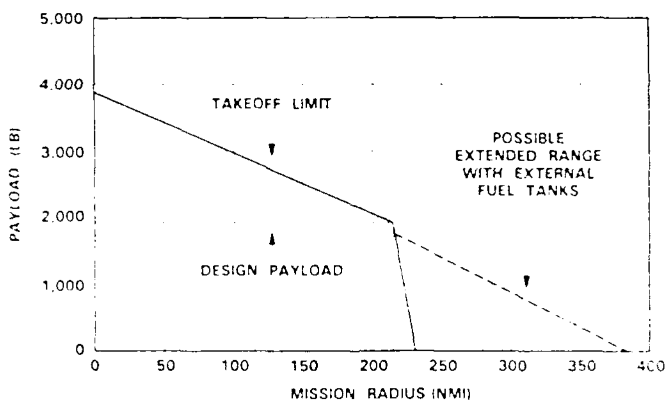
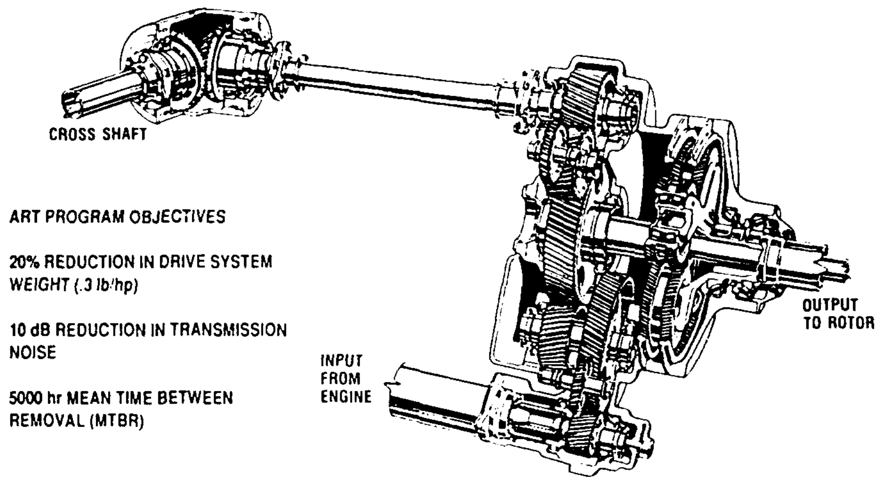


Figure 2 —Baseline aircraft mission performance

	WEIGHT	POTENTIAL FOR NOISE REDUCTION	POTENTIAL FOR MTBR INCREASE	PRODUCIBILITY & FABRICATION COMPLEXITY	RISK FACTOR	TOTAL RANK
SELF ALIGNING BEARINGLESS PLANETARY (SABP)	1	4	3	4	4	[illegible]
SPLIT TORQUE	4	2	2	2	2	[illegible]
SINGLE PLANETARY	3	[illegible]	1	3	[illegible]	[illegible]
WEIGHTING FACTOR	0.25	0.25	0.25	0.125	0.125	1.0

RANKING VALUE 1 MOST LIKELY TO ACHIEVE OBJECTIVES
4 HIGH PROBABILITY OF NOT ACHIEVING OBJECTIVES

Figure 3 --Total ranking - selection methodology



TACTICAL TILT ROTOR TRANSMISSION (LEFT SIDE)

Figure 4.—ART program TTR configuration.

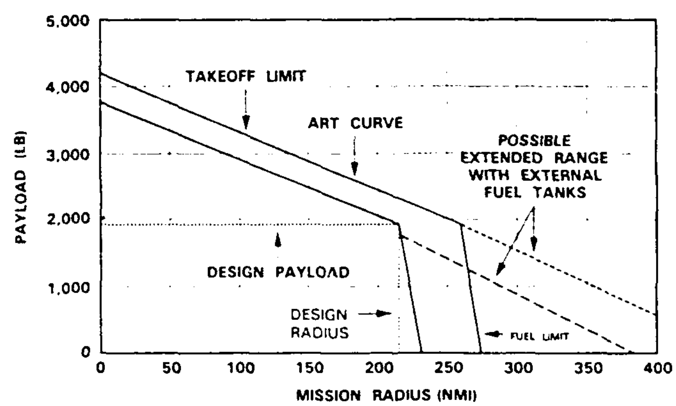


Figure 5.—ART A/C mission performance.

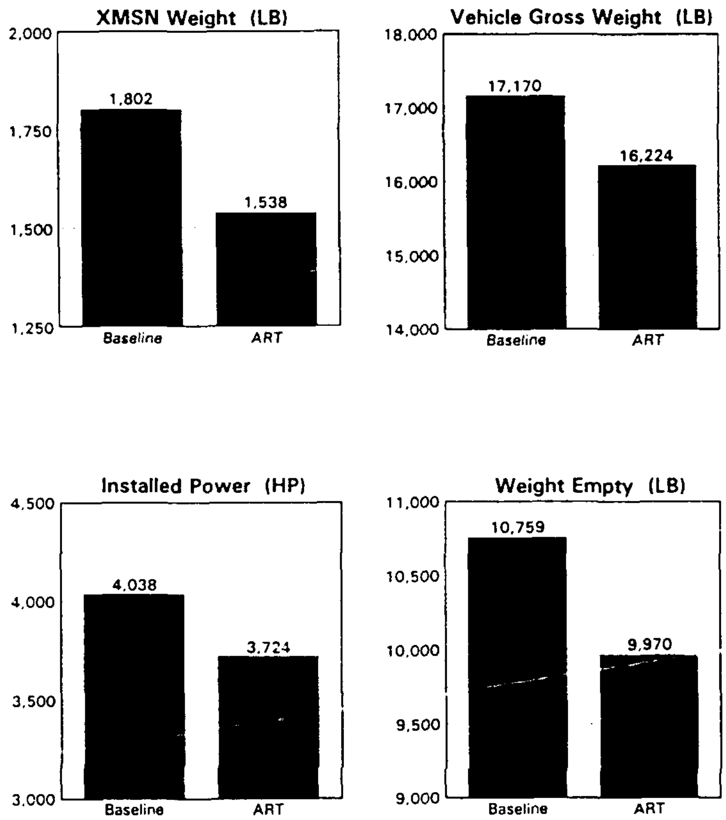


Figure 6.—ART effects on A/C design parameters.

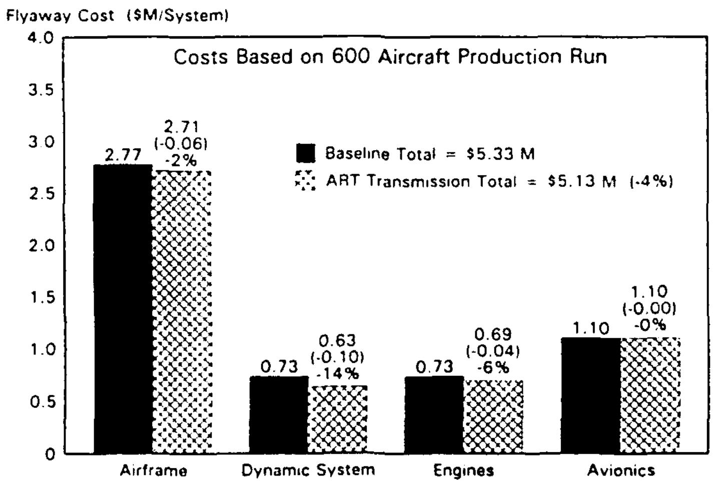


Figure 7.—Component group cost comparison.

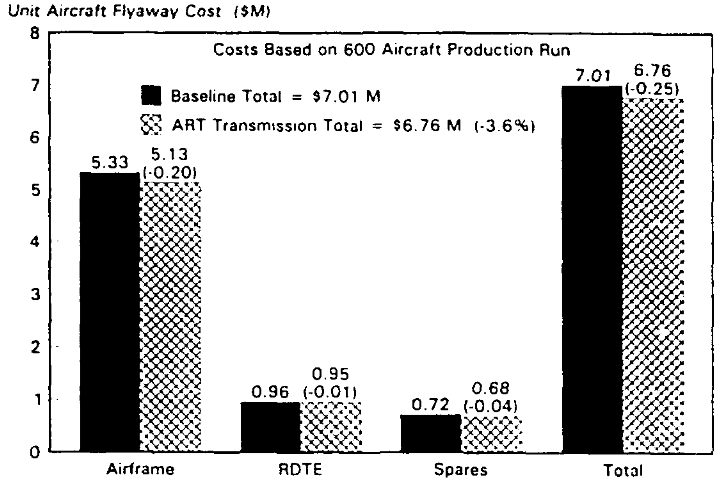


Figure 8.—Aircraft flyaway cost comparison.

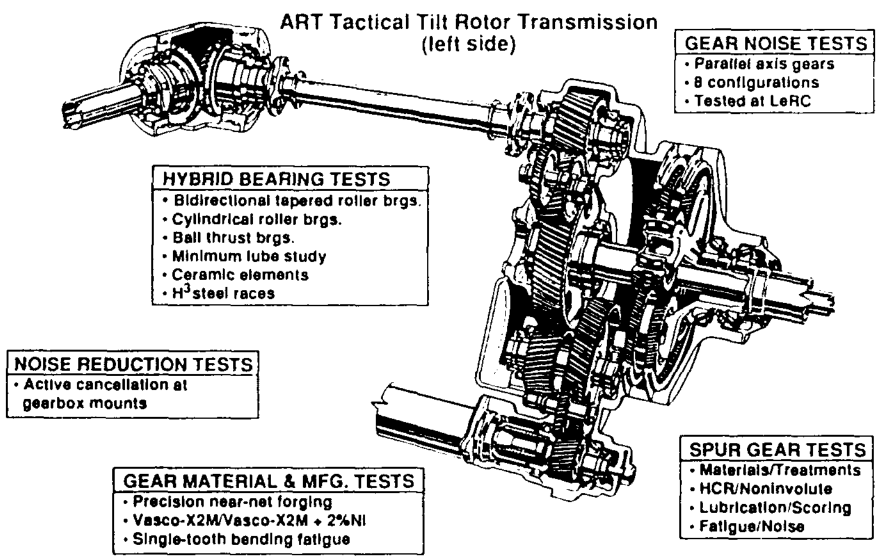


Figure 9.—Planned component testing.

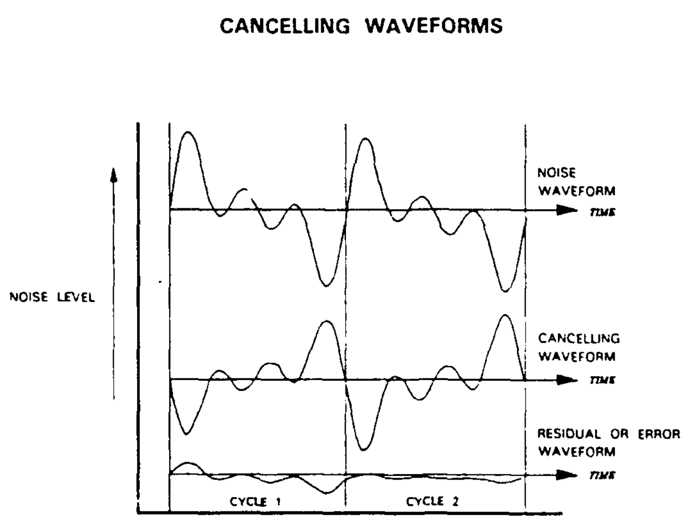


Figure 10.—Canceling wave forms.

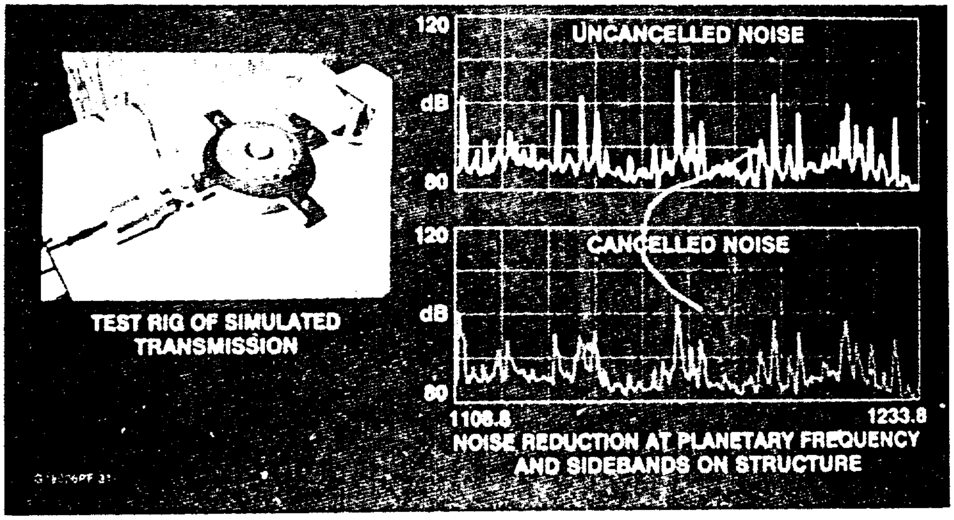


Figure 11.—Active noise cancellation results.

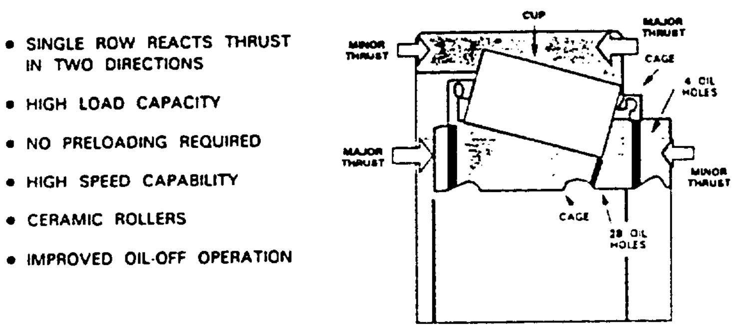


Figure 12.—Bidirectional tapered roller bearing.

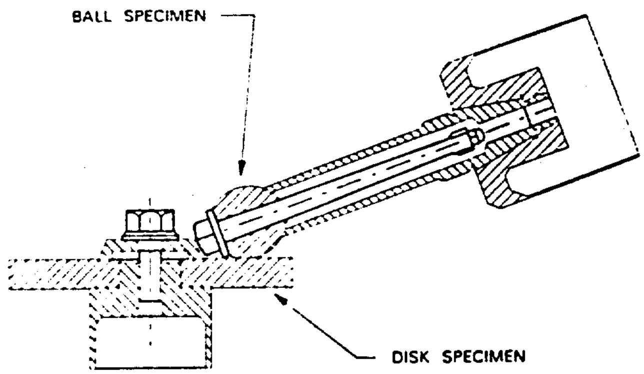


Figure 13.—Traction test rig.

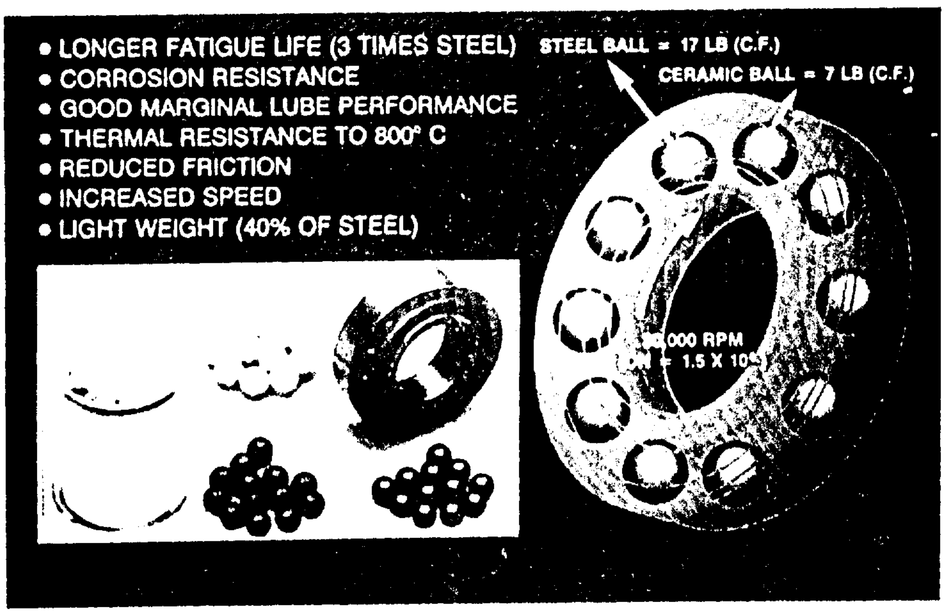


Figure 14.—Hybrid (ceramic) bearing.

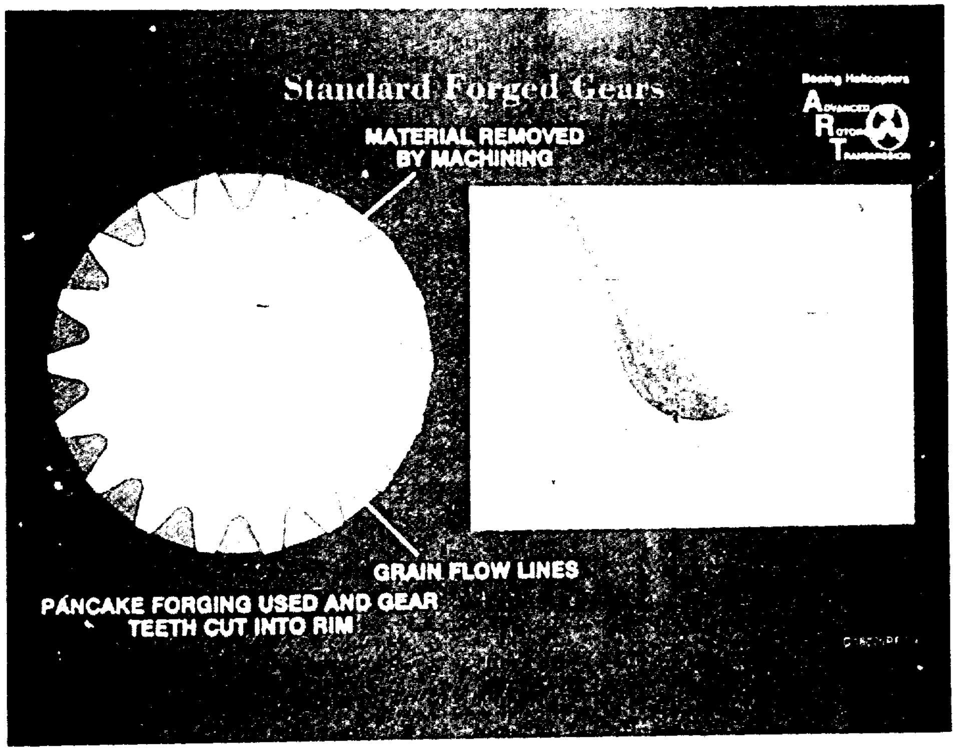


Figure 15.—Standard forged gears.

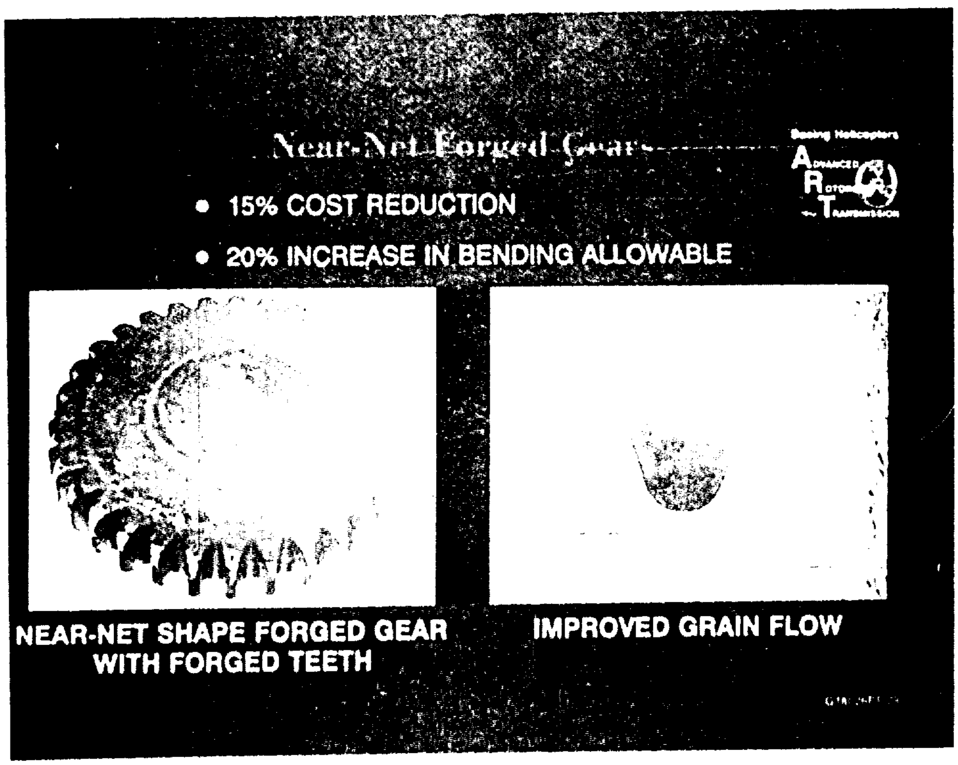


Figure 16.—Near net forged gears.

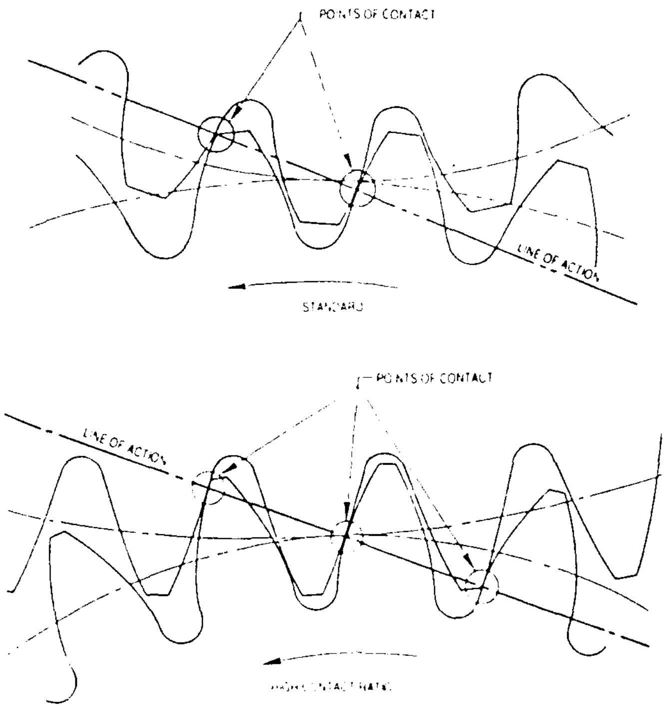
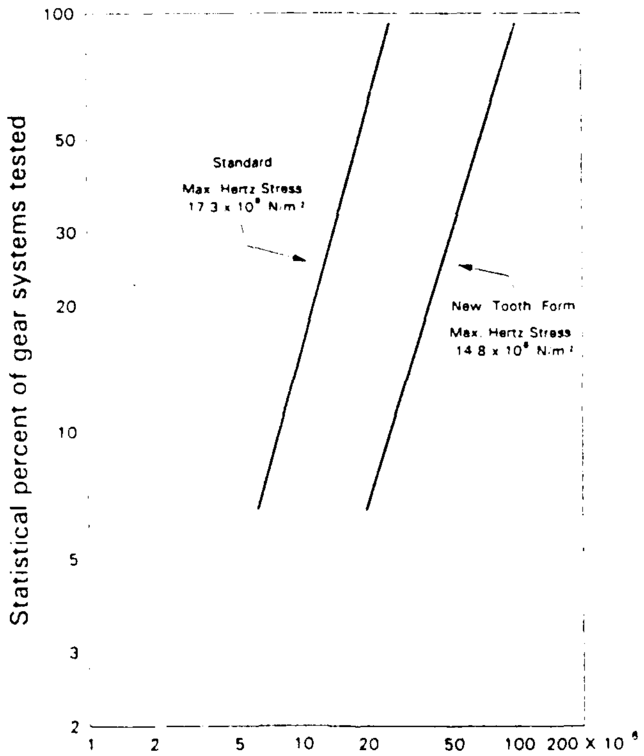


Figure 17 —Comparison of standard and high contact ratio contacts.



Gear Life, Cycles - Gear Life at Equal Loads. Load = 6,440 N/cm

Figure 18 —Surface durability, standard and HCR-NIF.

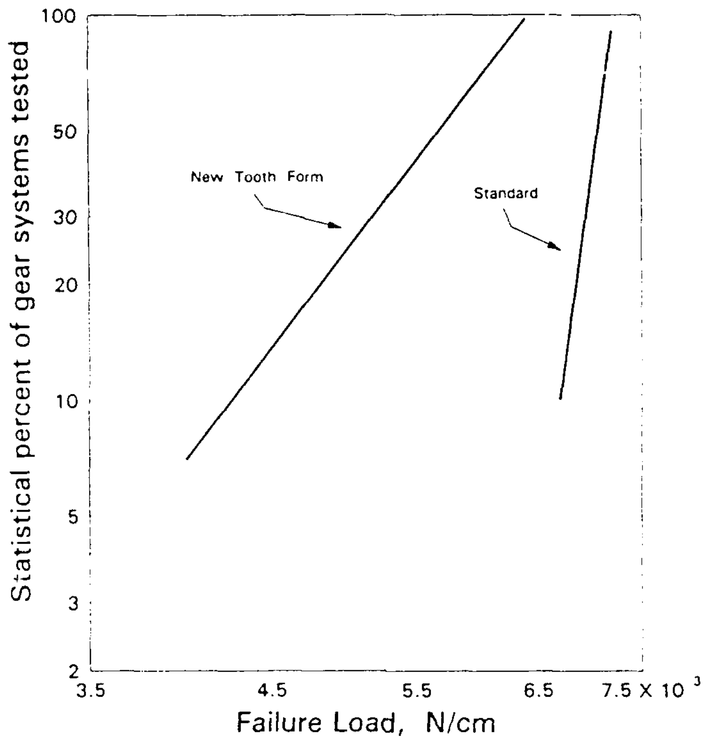


Figure 19.—Scoring, standard and HCR-NIF.

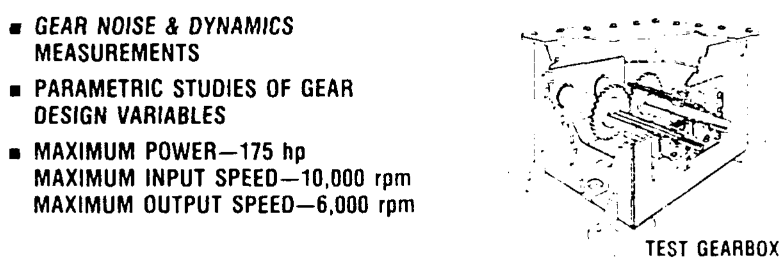


Figure 20.—NASA gear noise test rig.

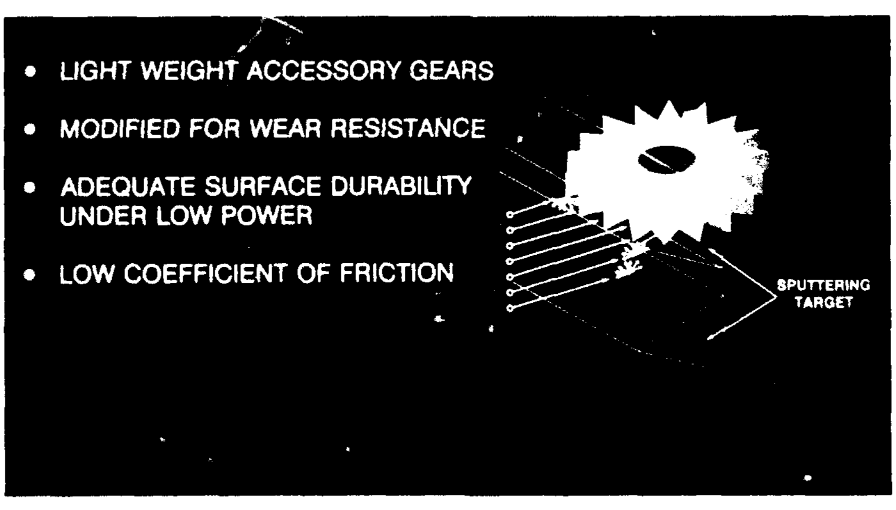


Figure 21.—Surface modified titanium gears.

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15. Supplementary Notes

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16. Abstract

On May 20, 1988, Boeing Helicopters was awarded a contract by the US Army Aviation Systems Command (AVSCOM) and the NASA Lewis Research Center to conduct the Advanced Rotorcraft Transmission (ART) program. The ART program is structured to incorporate key emerging material and component technologies into an advanced rotorcraft transmission with the intention of making significant improvements in the state-of-the-art (SOA). Specific objectives of the ART program are: (1) Reduce transmission weight by 25 percent relative to SOA trends (currently in the range of 0.4 lb/hp). (2) Reduce transmission noise by 10dB relative to SOA. (3) Improve transmission life and reliability, while extending Mean Time Between Removal (MTBR) to 5000 hr. The ART contract requires Boeing Helicopters to select a baseline transmission design that is representative of a SOA production design technology and then compare this design with the advanced configuration being developed during this program. Boeing Helicopters selected a transmission sized for the Tactical Tilt Rotor (TTR) aircraft which meets the Future Air Attack Vehicle (FAAV) requirements. Component development testing will be conducted to evaluate the high risk concepts prior to finalizing the advanced transmission configuration. A total of eight advanced technology component tests will be conducted: Noise reduction by active force cancellation; Hybrid bidirectional tapered roller bearings; Improved bearing life theory; Transmission lube study with hybrid bearings; Precision net forged spur gears; High profile contact ratio noninvolute tooth form spurgears; Parallel axis gear noise study; Surface modified titanium accessory spur gears. This paper summarizes the results of the trade-off studies and development tests which have been completed during the first three years of the contract.

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